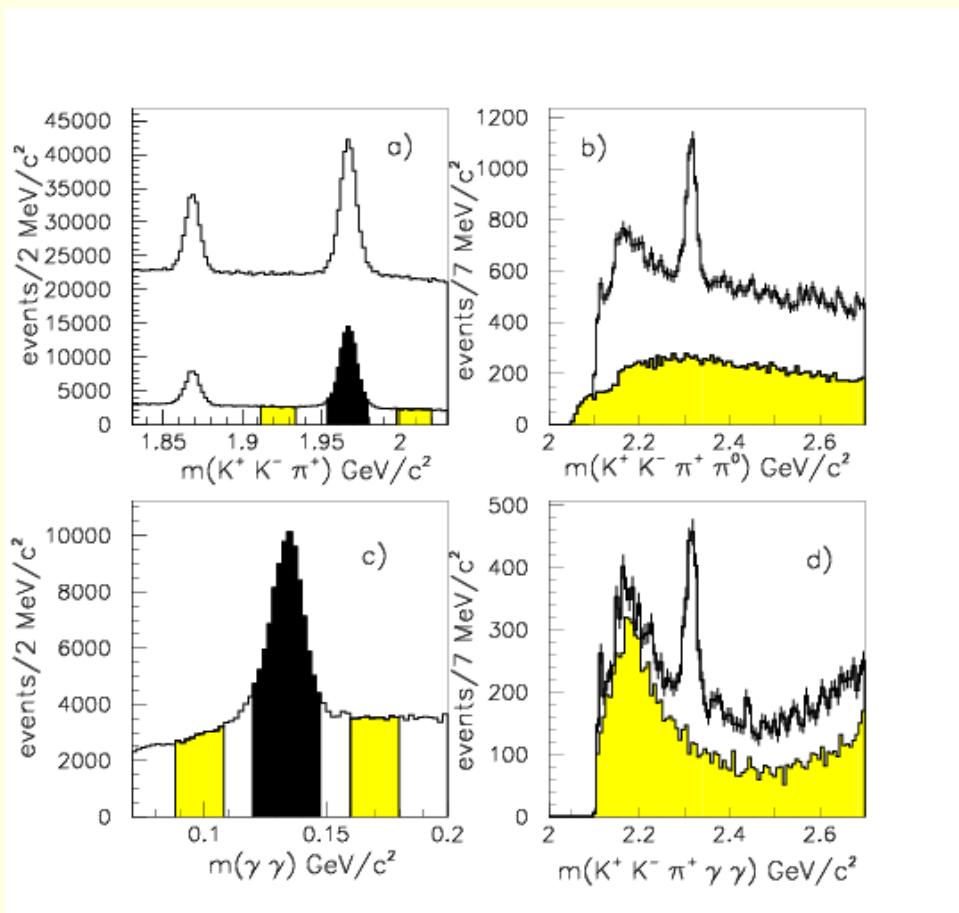


# The New $D_s$ States: The Hydrogen Atom Revisited

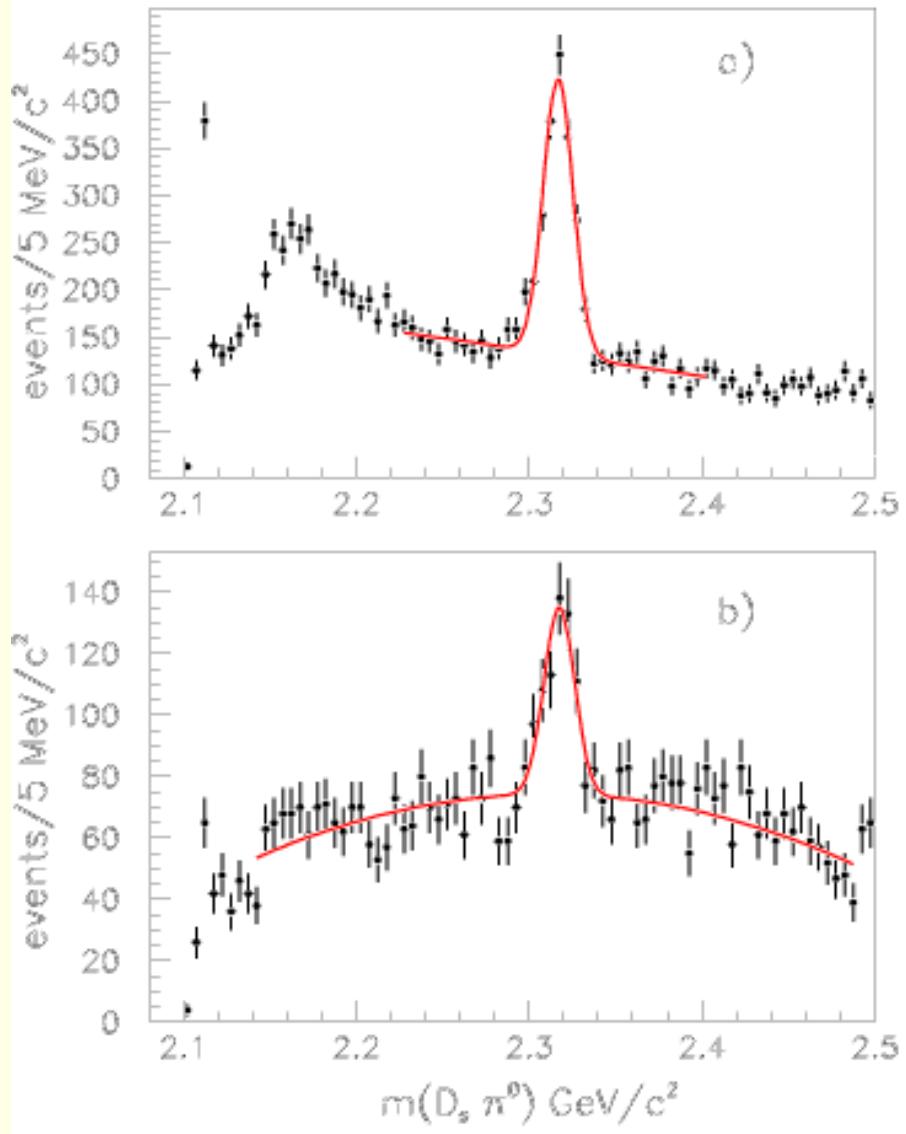
R. Cahn

September 8, 2003

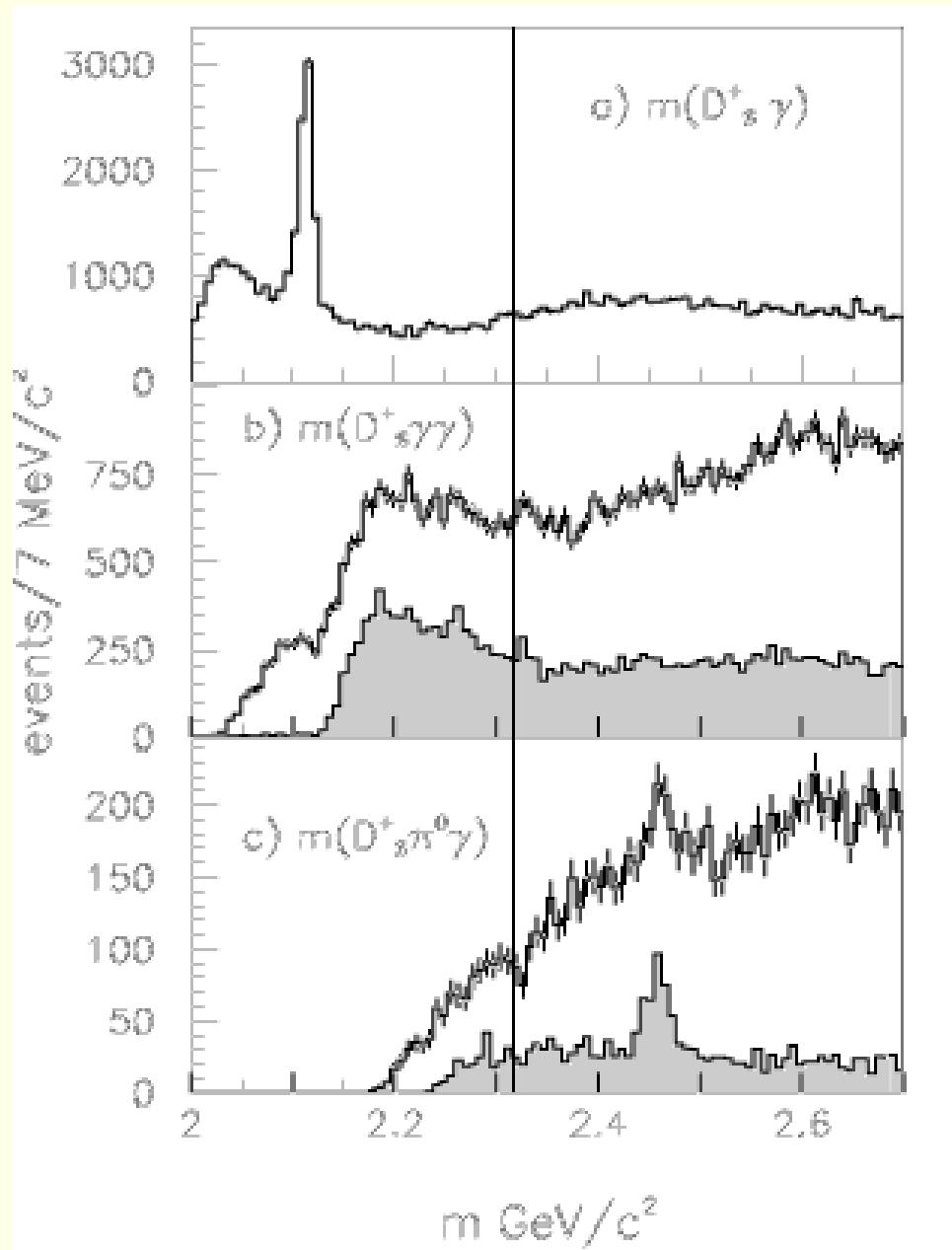
# BaBar Discovery of Narrow State Decaying to $D_s\pi^0$



- $\pi^0$  signal +  $D_s$  signal gives peak
- $\pi^0$  signal +  $D_s$  sideband gives no peak
- $\pi^0$  sideband +  $D_s$  signal gives no peak

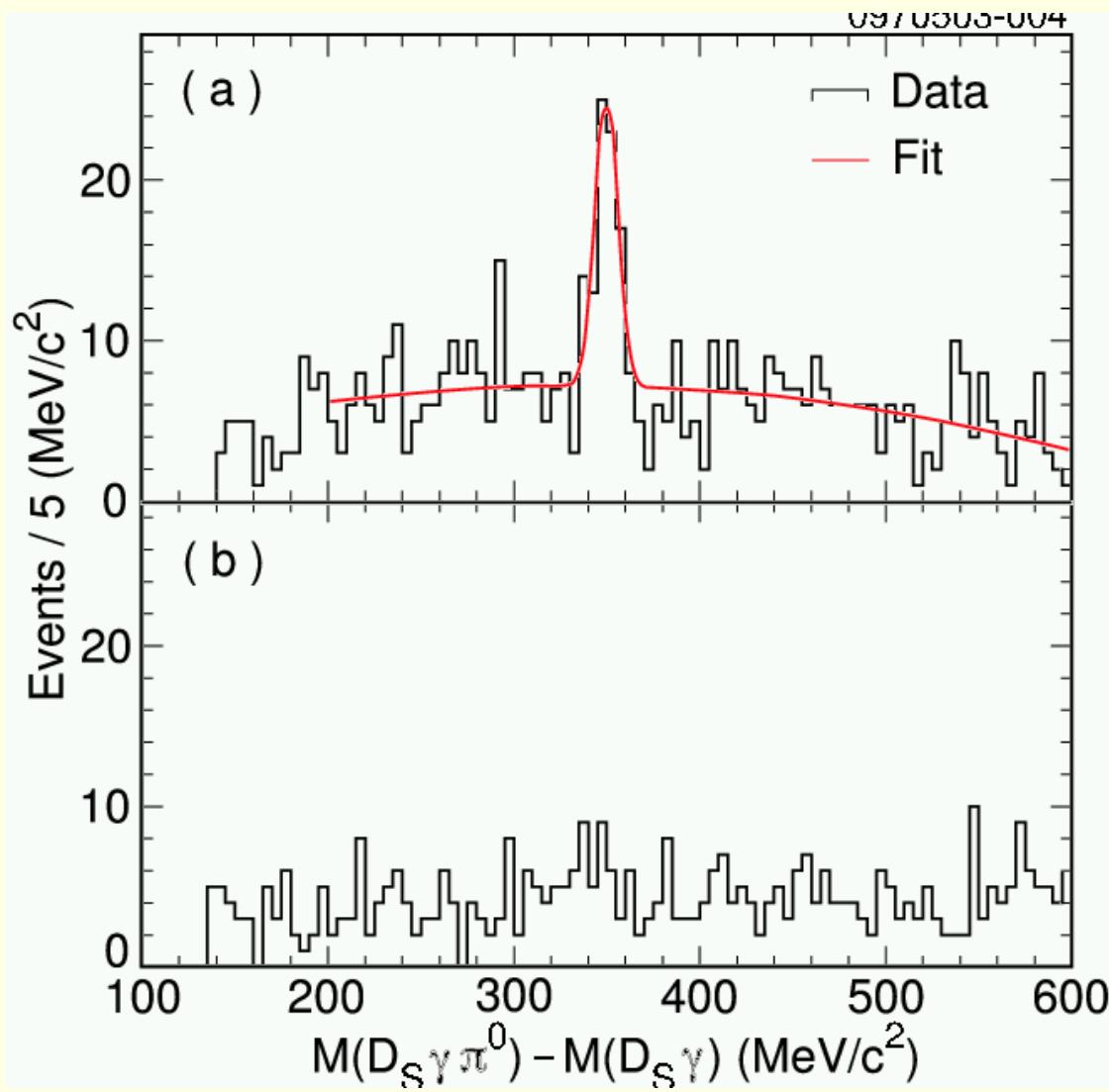


- $D_s\pi^0$  mass distribution for  $D_s \rightarrow K^+K^-\pi^+$
- $D_s\pi^0$  mass distribution for  $D_s \rightarrow K^+K^-\pi^+\pi^0$

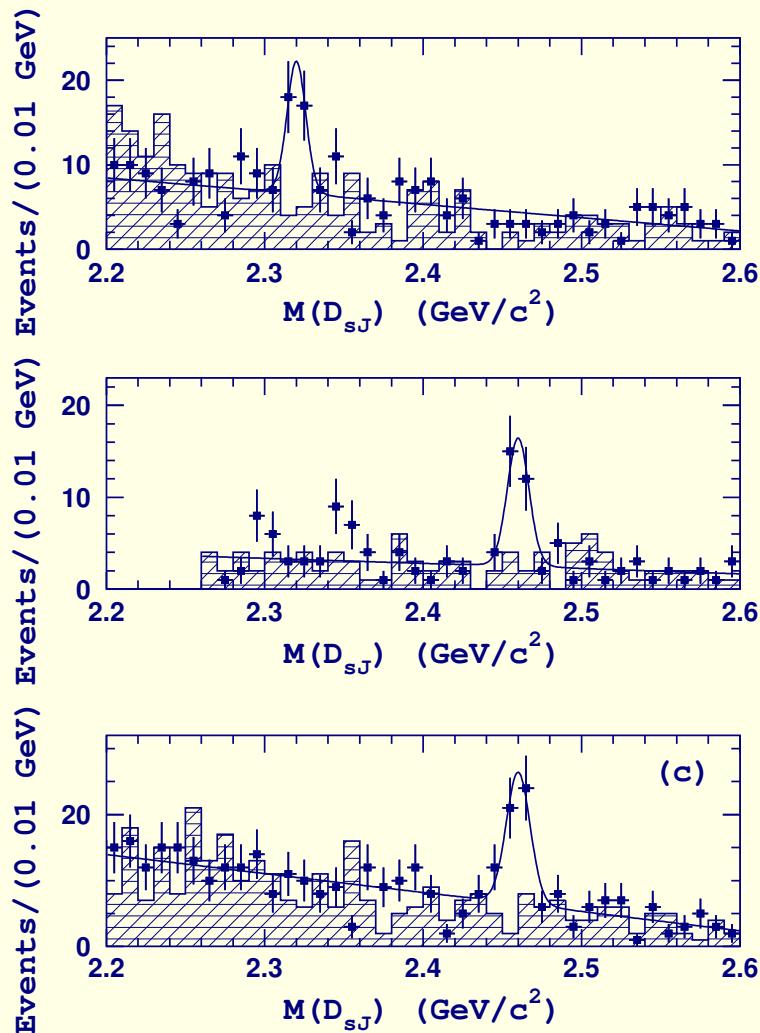


- No sign of  $D_{sJ}^*(2317) \rightarrow D_s \gamma$
- No sign of  $D_{sJ}^*(2317) \rightarrow D_s^* \gamma$
- Apparent structure in  $D_s \pi^0 \gamma$

# CLEO Discovers 2460



# Belle find exclusive decays



$B \rightarrow DD_{sJ}^*(2317)$

$D_{sJ}^*(2317) \rightarrow D_s \pi^0$

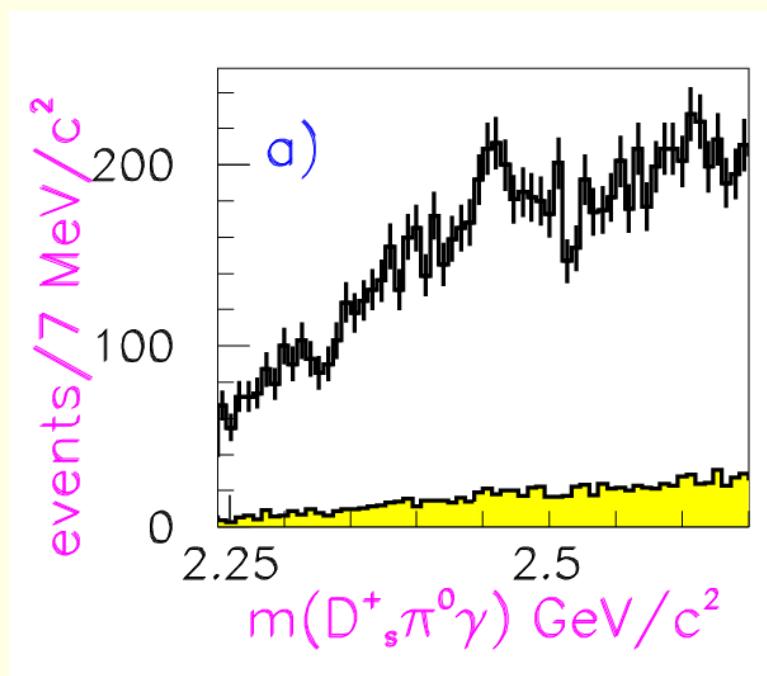
$B \rightarrow DD_{sJ}(2458)$

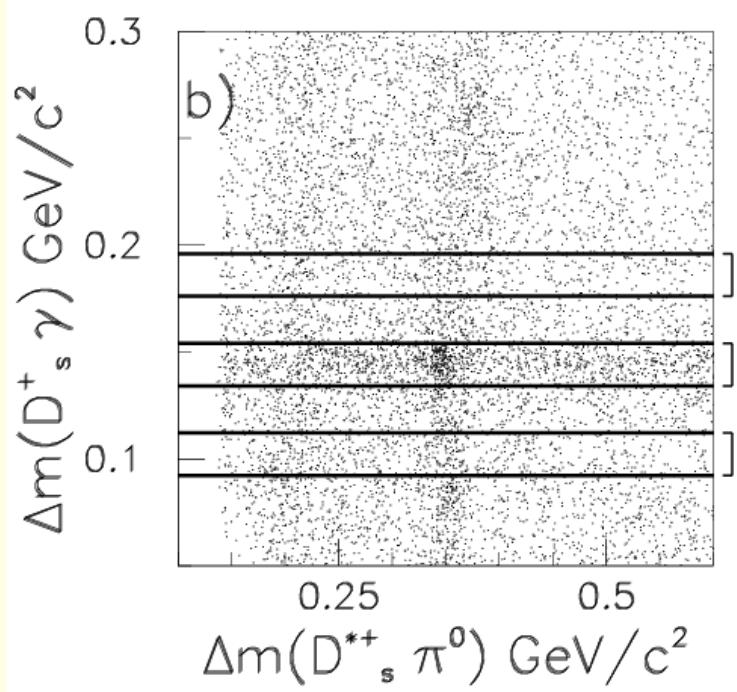
$D_{sJ}(2458) \rightarrow D_s \pi^0$

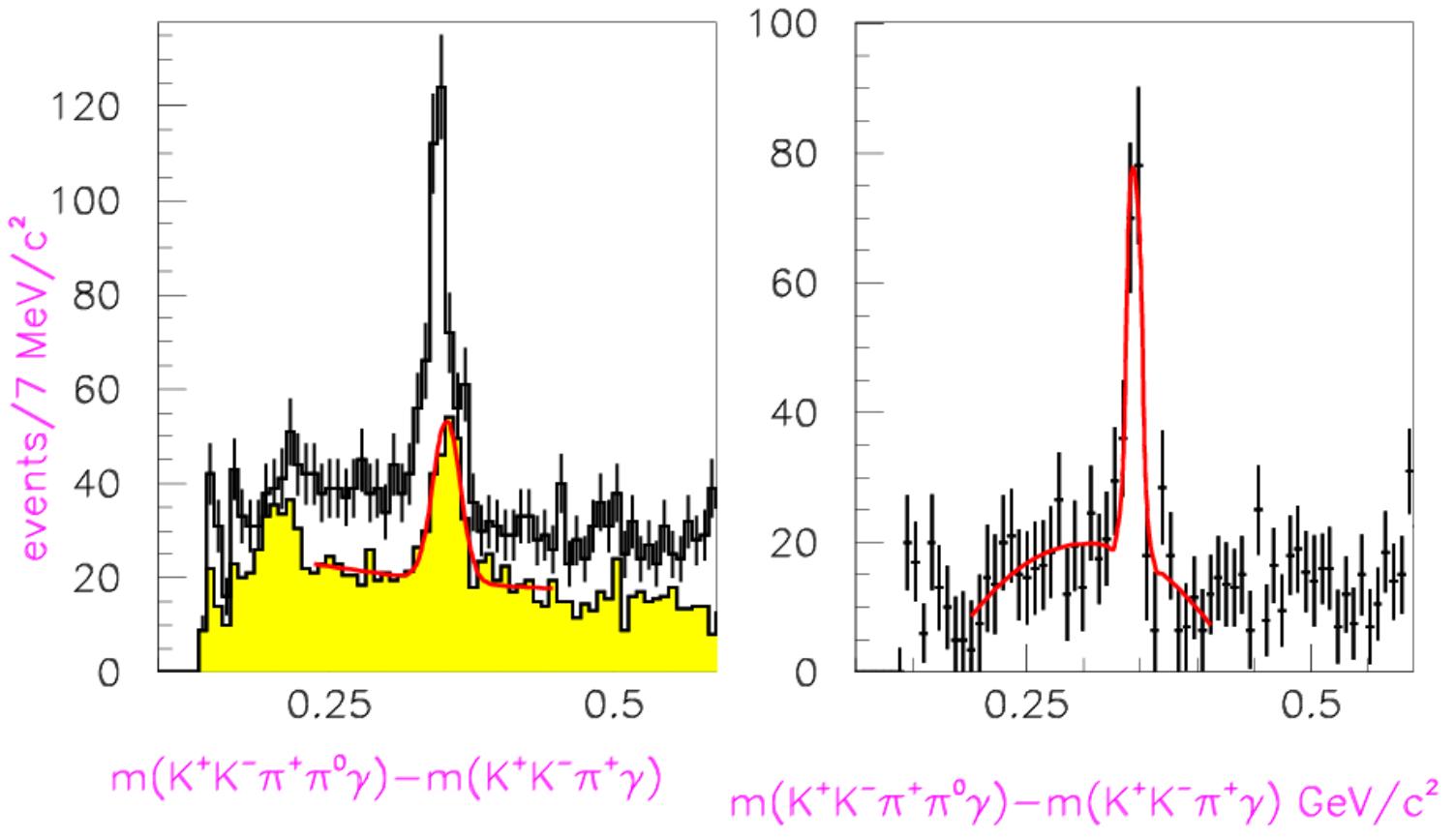
$B \rightarrow DD_{sJ}(2458)$

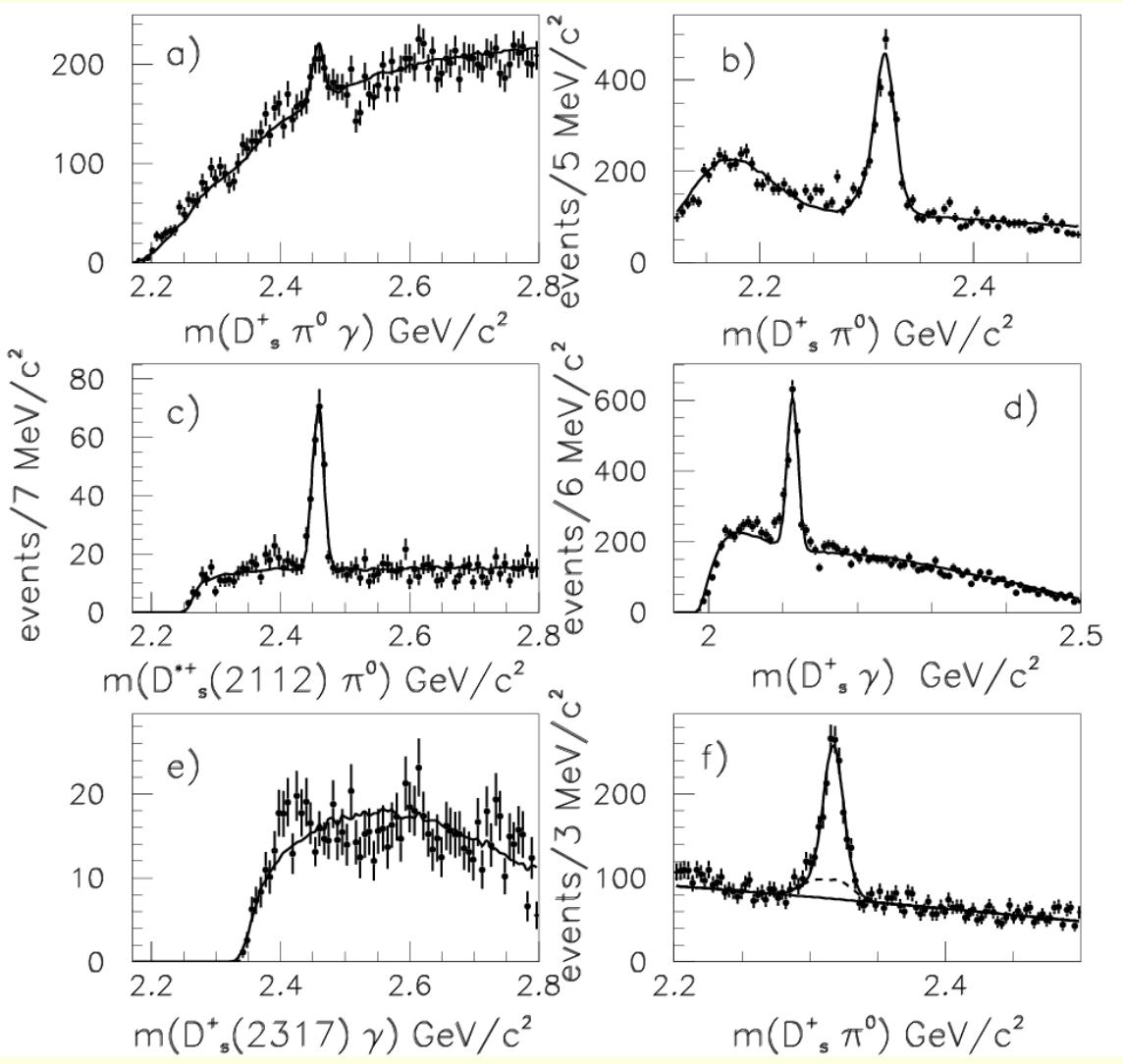
$D_{sJ}(2458) \rightarrow D_s \gamma$

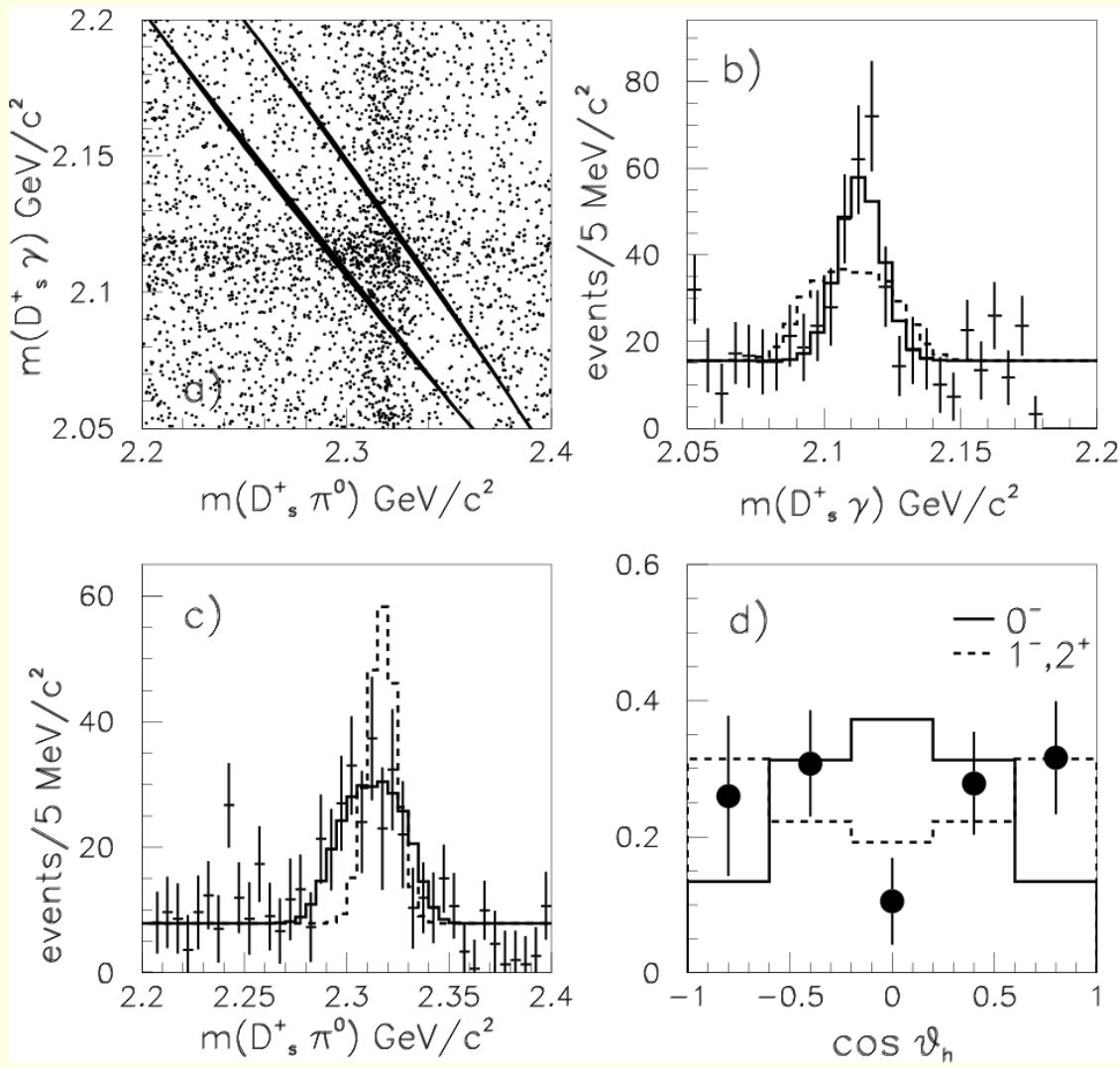
# BaBar results on $D_s(2458)$











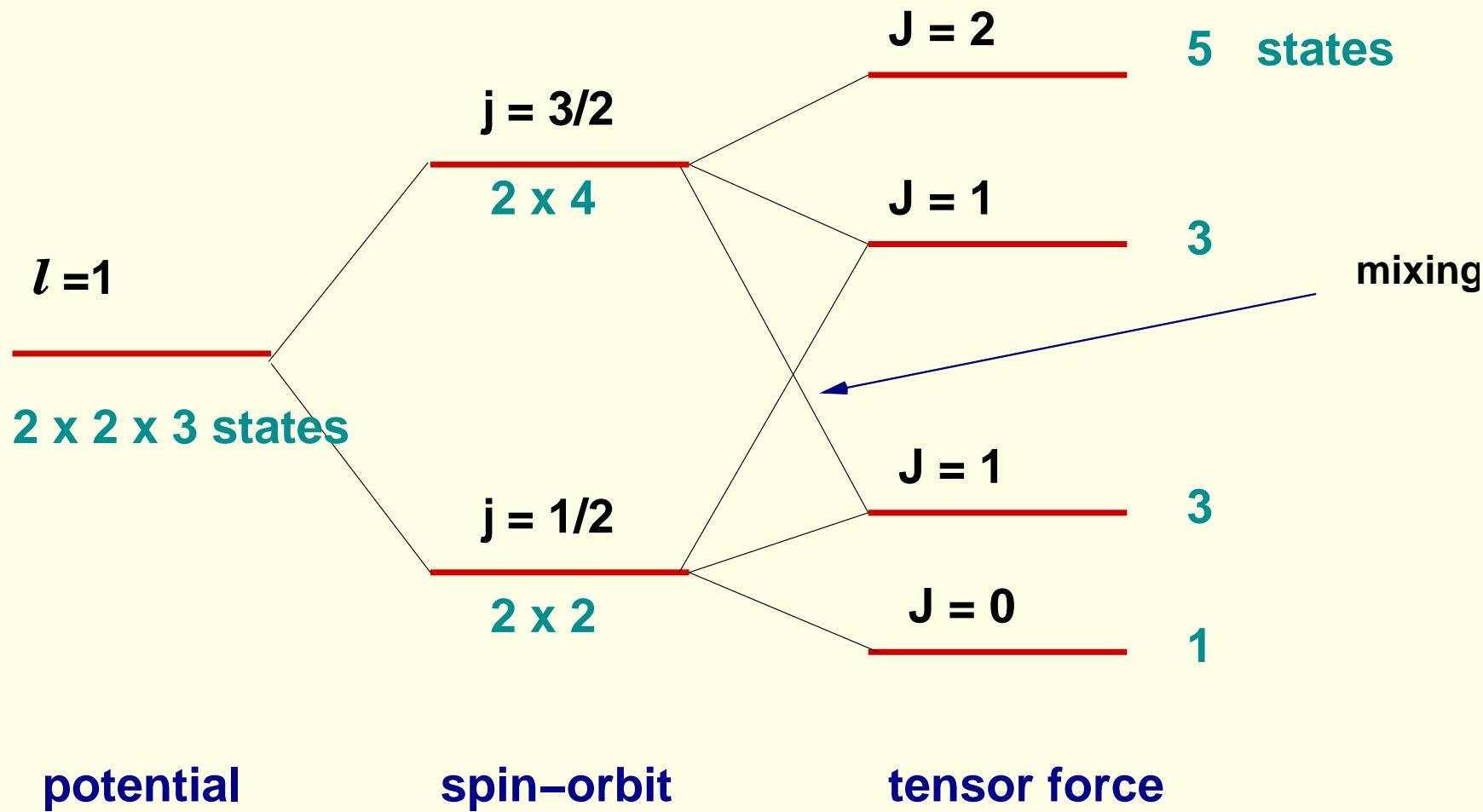
# Even CDF has something to say

# Heavy Quark - Light Quark Spectroscopy

## is the Hydrogen Atom

- First approximation: heavy quark is static source of potential
- Orbital angular momentum  $\ell$ , light-quark spin  $s$ , separately conserved
- Add spin-orbit interaction,  $\ell \cdot s$ 
  - $j = \ell + s$  conserved, not  $\ell, s$
- Add heavy quark, with spin  $S$ 
  - Interactions suppressed by  $m/M$
  - Spin-orbit interaction  $\ell \cdot S$
  - Spin-spin contact interaction  $s \cdot S \delta^3(r)$
  - Tensor force  $3S \cdot \hat{r} s \cdot \hat{r} - S \cdot s$
  - $J = j + S$  conserved, not  $j = \ell + s$

# p-wave states



# Canonical Approach

**DiPierro and Eichten, PRD 64, 114004 (2001)**

- Dirac equation with two potentials
  - Coulomb potential in fourth component of vector potential
  - Linear (confining) potential in scalar potential
- Solve Dirac equation with spin-orbit included
- Add tensor force (and small spin-orbit) perturbatively
- Fix coefficients of Coulomb and linear, masses of quarks to fit data from  $D$ ,  $D_s$ ,  $B$ ,  $B_s$  systems

# Predictions of DiPierro and Eichten

$J^P$	$D$		$D_s$	
	m(GeV) exp.	m(GeV) th	m(GeV) exp.	m(GeV) th
$S(J = 0)$	1.865	1.868	1.969	1.965
$S(J = 1)$	2.007	2.005	2.112	2.113
$P(J = 0)$	[2.290]	2.377		2.487
$P(J = 1)$	2.422	2.417	2.535	2.535
$P(J = 2)$	2.459	2.460	2.573	2.581
$P(J = 1)$	[2.400]	2.490		2.605

- The states  $D_0(2290)$  and  $D_1(2400)$  are from Belle at ICHEP and were not known at the time of the predictions.
- The same potentials are used for the  $D, D_s, B,$  and  $B_s$  systems.

# Decays and Selection Rules

- Angular momentum conserved: no  $0 \rightarrow 0\gamma$  decays
- Not weak decays: Parity conserved
  - $D_{sJ}^*(2317) \rightarrow D_s(0^-)\pi^0$  forces natural spin-parity for  $D_{sJ}^*(2317)$  [ $0^+, 1^- \dots$ ]
  - $D_{sJ}^*(2317) \rightarrow D_s^*(1^-)\pi^0$  forbidden if  $D_{sJ}^*(2317)$  is  $0^+$
- Isospin mostly conserved
  - $D_{sJ}^*(2317) \rightarrow D_s(0^-)\pi^0$  violates isospin
  - $D_s^*(2112) \rightarrow D_s(0^-)\pi^0$  violates isospin, 5% of  $D_s(2112) \rightarrow D_s(0^-)\gamma$
  - $D_s?(2460?) \rightarrow D_s(0^-)(\pi\pi)_{L=0}$  allowed if  $1^+$ , needs p-wave
  - $D_{s2}(2575) \rightarrow DK$  d-wave,  $\rightarrow D^*K$  d-wave
  - $D_{s1}(2535) \rightarrow D^*K$  s-wave, d-wave

- Light-quark angular momentum ( $j = \ell + s$ ) nearly conserved
  - $D_{s1}(2535)$  mostly  $j = 3/2$ ,  $D(2007)$  all  $j = 1/2$
  - $D_{s1}(2535) \rightarrow D(2007)K$  d-wave not s-wave ( $\Gamma < 2.3$  MeV)
  - $D(J = 1, j = 1/2)$  should be broad

- Isospin violation
  - Violated by electromagnetism
  - Violated by  $m_u \neq m_d$
  - Scale is  $(m_u - m_d)/\Lambda_{QCD} \ll 1$

# Chiral Symmetry and Isospin Violation

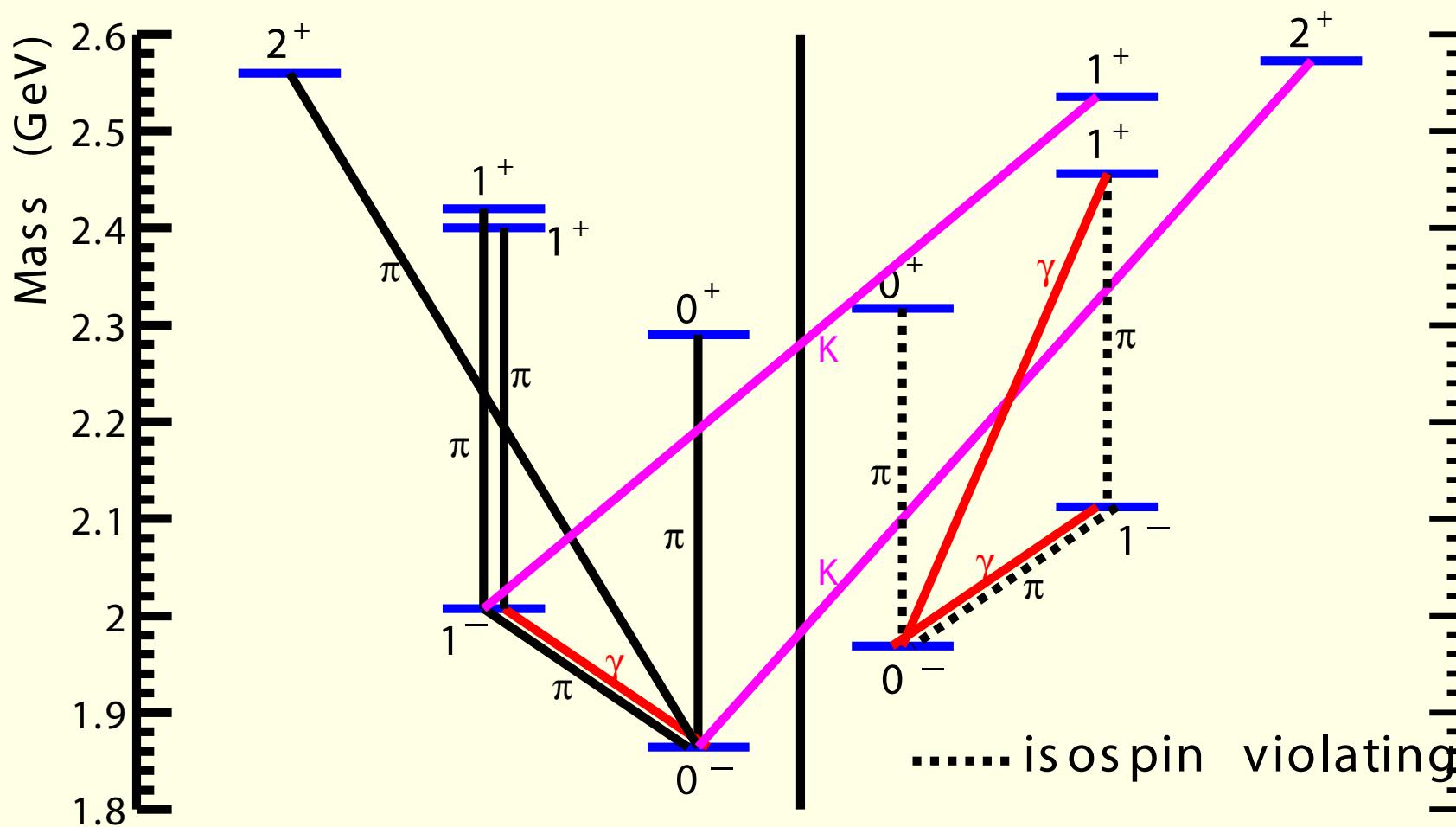
$$\Pi = \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & \frac{\pi^0}{\sqrt{2}} - \frac{\eta}{\sqrt{6}} & K^0 \\ K^- & \bar{K}^0 & -\frac{2}{\sqrt{6}}\eta \end{pmatrix}; \quad M = \begin{pmatrix} m_u & 0 & 0 \\ 0 & m_d & 0 \\ 0 & 0 & m_s \end{pmatrix}$$

Mass-squared term from  $\text{Tr } \Pi M \Pi$  leads to  $\pi^0 - \eta$  mixing, with mixing angle

$$\tan \theta = \frac{\sqrt{3}}{2} \frac{m_d - m_u}{m_s - (m_u + m_d)/2}$$

Use  $\frac{m_{K^+}^2 - m_{\pi^+}^2}{m_{K^0}^2 - m_{\pi^0}^2} = \frac{m_s - m_d}{m_s - m_u}; \quad \frac{m_\eta^2}{m_{\pi^0}^2} = \frac{(4m_s + m_u + m_d)/3}{m_u + m_d}$

to find  $m_s/m_d = 20$ ,  $m_u/m_d = 0.55$ ,  $\tan \theta \approx 1/50$

$D^{0,+}$  $D_s^+$ 

# “Almost-Model-Independent” Spectroscopic Predictions (J. D. Jackson & RNC: hep-ph/0305012)

- Potential includes  $V$  and  $S$
- $V$  is Coulombic, as suggested by QCD
  - Fourth component of vector potential
- $S$  is linear, confining
  - Scalar, not fourth component of vector potential
- Determine potentials from Feynman diagram, expand in  $v/c$

# Effective Interaction

$$\begin{aligned}\mathcal{V}_{quasi-static} = & V + S + \left( \frac{V' - S'}{r} \right) \boldsymbol{\ell} \cdot \left( \frac{\boldsymbol{\sigma}_1}{4m_1^2} + \frac{\boldsymbol{\sigma}_2}{4m_2^2} \right) + \left( \frac{V'}{r} \right) \boldsymbol{\ell} \cdot \left( \frac{\boldsymbol{\sigma}_1 + \boldsymbol{\sigma}_2}{2m_1 m_2} \right) \\ & + \frac{1}{12m_1 m_2} \left( \frac{V'}{r} - V'' \right) S_{12} + \frac{1}{6m_1 m_2} \nabla^2 V \cdot \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2\end{aligned}$$

- If  $V$  is Coulombic  $-V'' + V'/r = 3V'/r$
- To order  $1/m_2$ :  $M = \lambda \boldsymbol{\ell} \cdot \boldsymbol{s}_1 + 4\tau \boldsymbol{\ell} \cdot \boldsymbol{s}_2 + \tau S_{12}$

$$\lambda = \frac{1}{2m_1^2} \left[ \frac{V'}{r} \left( 1 + \frac{2m_1}{m_2} \right) - \frac{S'}{r} \right] \quad \tau = \frac{1}{4m_1 m_2} \frac{V'}{r}.$$

# Quantum Mechanics in Action

- Can diagonalize commuting variables
- One choice:  $J^2, j'^2, J_z$
- Another:  $J^2, j'^2, J_z \quad j' = \ell + s_2$
- Yet another:  $J^2, S^2, J_z \quad S = s_1 + s_2$
- Must be possible to express one basis in terms of another
- Calculate  $\ell \cdot s_1$  in first basis
- Calculate  $\ell \cdot s_s$  in second basis
- Calculate  $S_{12}$  in third

# Masses of the Four P states

$$\begin{aligned} M_2 &= \frac{\lambda}{2} + \frac{5}{8}\tau \\ M_0 &= -\lambda - 8\tau \end{aligned}$$

Masses of the two  $J = 1$  state from diagonalizing in the  $|Jjm\rangle$  basis

$$\begin{pmatrix} \frac{\lambda}{2} - \frac{8}{3}\tau & -\frac{2\sqrt{2}}{3}\tau \\ -\frac{2\sqrt{2}}{3}\tau & -\lambda + \frac{8}{3}\tau \end{pmatrix} \quad (1)$$

The two eigenmasses for  $J = 1$  are then

$$\begin{aligned} M_{1+} &= -\frac{\lambda}{4} + \sqrt{\frac{\lambda^2}{16} + \frac{1}{2}(\lambda - 4\tau)^2} \\ M_{1-} &= -\frac{\lambda}{4} - \sqrt{\frac{\lambda^2}{16} + \frac{1}{2}(\lambda - 4\tau)^2} \end{aligned}$$

# Use Three Measured States to Predict Fourth

$$D_2 = M_2 - M_0$$

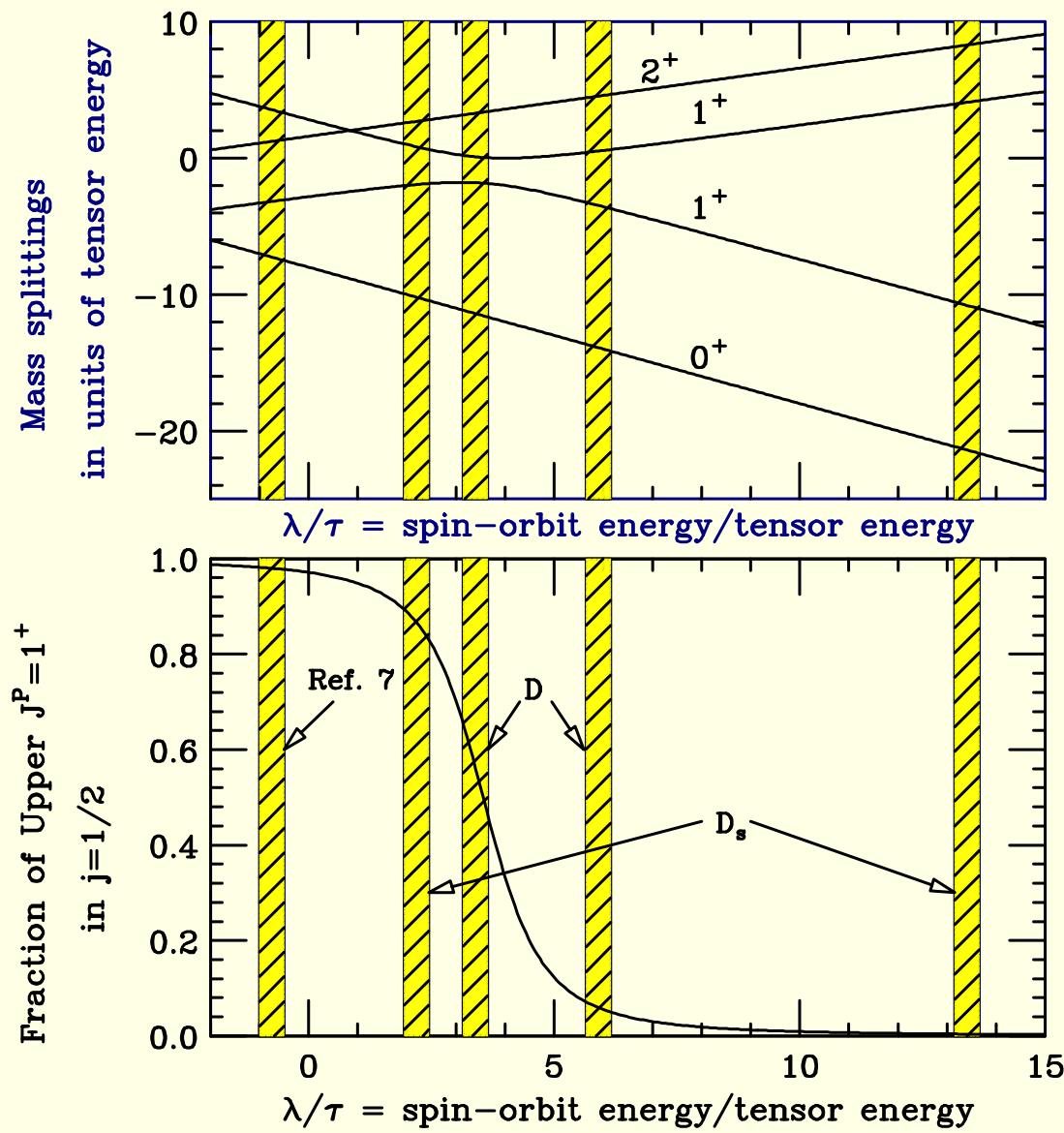
$$D_1 = M_{1-} - M_0$$

we find

$$\tau = \frac{10}{87}D_2 - \frac{2}{29}D_1 \pm \sqrt{\left(\frac{10}{87}D_2 - \frac{2}{29}D_1\right)^2 + \frac{5}{232}(D_1^2 - D_1D_2)}$$

and

$$\lambda = \frac{2}{3}D_2 - \frac{32}{5}\tau$$



# Masses in $D$ and $D_s$ P States

	Exp.	Theory		
		Sol. A	Sol. B	DiPierro-Eichten
<i>D</i> mesons				
$M(2^+)(\text{GeV})$	2.459	[2.459]	[2.459]	2.460
$M(1^+)(\text{GeV})$	2.400	2.400	2.385	2.490
$M(1^+)(\text{GeV})$	2.422	[2.422]	[2.422]	2.417
$M(0^+)(\text{GeV})$	2.290	[2.290]	[2.290]	2.377
$\lambda$ (MeV)		39	54	-11
$\tau$ (MeV)		11	9	+11
<i>D<sub>s</sub></i> mesons				
$M(2^+)(\text{GeV})$	2.572	[2.572]	[2.572]	2.581
$M(1^+)(\text{GeV})$		2.480	2.408	2.605
$M(1^+)(\text{GeV})$	2.536	[2.536]	[2.536]	2.535
$M(0^+)(\text{GeV})$	2.317	[2.317]	[2.317]	2.487
$\lambda$ (MeV)		43	115	-7
$\tau$ (MeV)		20	9	+11

# Widths in $D$ and $D_s$ P States

	Exp.	DiPierro-Eichten pure s-wave	pure d-wave
<b><math>D</math> mesons</b>			
$D_2^*(2460) \rightarrow D(1865)\pi$	$23 \pm 5$		16
$D_2^*(2460) \rightarrow D^*(2007)\pi$	$23 \pm 5$		9
$D_1(2422) \rightarrow D^*(2007)\pi$	$18.9^{+4.6}_{-3.5}$	94	10
$D_1(2400) \rightarrow D^*(2007)\pi$	$380 \pm 100 \pm 100$	100	
$D_0^*(2290)$	$305 \pm 30 \pm 25$	100	
<b><math>D_s</math> mesons</b>			
$D_2^*(2573) \rightarrow D(1865)K$	$15^{+5}_{-4}$		8.9
$D_2^*(2573) \rightarrow D^*(2007)K$	$15^{+5}_{-4}$		1.4
$D_1(2535) \rightarrow D^*(2007)K$	$< 2.3$	100	0.3

# Choosing Solutions

- Need nearly pure  $j = 3/2$  to suppress  $D_1(2422)$ ,  $D_s(2535)$  decays
- Forces solutions with large  $\lambda/\tau$
- Contrary to “traditional picture.”

# Alternative Views: Molecules not Atoms

- Barnes, Close, and Lipkin [hep-ph/0305025]
- Bound  $DK$ , near threshold
- Might be isovectors, too. Look for  $D_s\pi^\pm$
- Expect to find regular  $c\bar{s}$  states as well

# Alternative Views

## Chiral Symmetry + Heavy Quark Symmetry

- Bardeen, Eichten, and Hill [hep-ph/030549]
- If chiral symmetry good  $(0^-, 1^-)$  degenerate with  $(0^+, 1^+)$
- Predicted roughly 340 MeV splitting, new  $1^+$  at 2460!
- Predict
  - $\Gamma((D_s(0^+) \rightarrow D_s^*(1^-)\gamma) = 1.7 \text{ keV}$
  - $\Gamma((D_s(0^+) \rightarrow D_s^*(0^-)\pi^0) = 22 \text{ keV}$
  - $\Gamma((D_s(1^+) \rightarrow D_s(0^-)\gamma) = 5 \text{ keV}$
  - $\Gamma((D_s(1^+) \rightarrow D_s(1^-)\pi^0) = 22 \text{ keV}$
  - $\Gamma((D_s(1^+) \rightarrow D_s(0^-)\pi\pi) = 4 \text{ keV}$
  - $\Gamma((D_s(1^+) \rightarrow D_s(0^+)\gamma) = 3 \text{ keV}$

# Summary

- BaBar results on  $D_s\pi^0$  contradict theoretical predictions
- Belle results on  $D$  somewhat contradict theoretical predictions
- Can fit p-wave masses, but with bigger spin-orbit energy than expected
- To suppress decay rate of  $1^+$  states need to take extremely large spin-orbit energy
- BaBar results will profoundly affect heavy-quark light-quark spectroscopy